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TECHNICAL PAPER proposed for presentation at Third Annual Metrology Converence sponsored by the Precision Measurements Association
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Abstract

An experimental investigation was performed to examine a fluidic oscillator to sense molecular-weight of flowing gases having molecular weights from 4 to 83.8. Data were taken using four monatomic gases (helium, neon, argon, and krypton) and five polyatomic gases (carbon dioxide, air, nitrogen, propane, and methane). Gas mixtures of hydrogen-nitrogen and helium-xenon were also investigated. From test results, it was observed that for choked flow or constant pressure drop, the oscillator frequency is proportional to the sonic velocity of the gas. However, the monatomic and polyatomic gases have a different constant of proportionality. The effect of changes in pressure drop and temperature on oscillator frequency is also discussed.

1. INTRODUCTION

Gas mixtures are being used in closed-cycle space power generating systems such as the Brayton cycle system (ref. 1). Small changes in the molecular weight of the gas mixture can cause significant changes in operating characteristics of turbomachinery and overall system performance. To alleviate this problem, a simple but reliable device is needed that will continuously monitor a flowing gas mixture and produce a signal related to the molecular weight of the gas mixture. This report contains the results of experimental investigations showing that a fluidic oscillator can be used as a molecular weight sensor of flowing gases.

Two fluidic oscillators were evaluated. The first oscillator was used to detect changes in molecular weight of gas mixtures, hydrogen-nitrogen and helium-xenon (ref. 2). The second oscillator, of a different design, was evaluated using nine individual gases of known molecular weight (ref. 3). The nine gases included four monatomic gases (helium, neon, argon and krypton) and five polyatomic gases (nitrogen, dry air, carbon dioxide, propane and methane).

For the majority of the tests, the gas temperature was ambient and pressure drop across the oscillator was held constant. Gas inlet pressures were less than 45 psia (30 N/cm^2) and the gas leaving the oscillator was exhausted to atmosphere. Tests were also conducted to see what effects changes in pressure drop across the oscillator and changes in inlet gas temperature had on oscillator output frequency.

2. APPARATUS AND TEST PROCEDURE

A fluidic oscillator can be defined as a fluidic bistable element with feedback to cause switching of the main jet. In the two oscillators tested, the frequency of switching is caused by a pressure pulse that propagates through the feedback line at sonic velocity. Additional information

about fluidic oscillators is presented in references 3, 4, and 5.

Two oscillators were examined. Figure 1A shows a schematic diagram of oscillator No. 1 which was developed by the Research Laboratories Division of the Bendix Corporation as a humidity sensor for Lewis Research Center (ref. 6). This oscillator was evaluated with gas mixtures of helium-xenon and of hydrogen-nitrogen. A schematic diagram of the test rig is shown in figure 1B.

Tests were conducted at ambient temperature. The molecular weight of each gas mixture was calculated from the measured flow rates. The flow rates of the gases were independently measured by using calibrated orificies in the "choked" condition for which flow is proportional to upstream pressure. Pressure transducers were used to measure pressure upstream of the orifices and were calibrated before each test. Flow of each gas was regulated by control valves, and the two gases were mixed before flowing through the fluidic oscillator. The pressure drop across the fluidic oscillator was kept constant by regulating the bypass flow valve (automatic control). For the helium-xenon gas mixture, pressure drop was maintained at 5.0 psi (3.4 N/cm^2) and a pressure drop of 6.0 psi (4.1 N/cm^2) was maintained during the testing of the hydrogen-nitrogen mixture. The frequency of oscillation was recorded by a piezoelectric pressure transducer connected to a charge amplifier and read out on an electronic counter.

The second oscillator (fig. 2A) was designed and fabricated at the Lewis Research Center to obtain higher frequencies of oscillation and thus greater output sensitivity than oscillator No. 1. This was accomplished by designing a feedback channel length of 2 inches (5 cm) compared to 5-3/4 inch (14.6 cm) feedback channel in oscillator No. 1. Since gas mixtures were tested with oscillator No. 1, the second oscillator was evaluated using gases of known molecular weight. This procedure simplified the test rig configuration as shown in figure 2B. The pressure drop across the oscillator was varied from approximately 6 to 30 psi (4 to 21 N/cm^2) by controlling a hand valve upstream of the fluidic oscillator. Gas pressures at the oscillator inlet and outlet were observed on calibrated pressure gages, but no internal pressure changes could be measured. Gas flow was obtained from a calibrated rotameter (0 to 92 standard ft^3/hr or 0 to 2.6 standard m^3/hr) before being exhausted to the atmosphere. The frequency of oscillation was sensed by a piezoelectric transducer inserted into one of the feedback loops to measure the pressure pulses. This transducer was connected to a charge amplifier in which the pressure pulse was converted to a frequency signal and read out on a counter to within an accuracy of 2 hertz.

Nine gases were used as working fluids at constant temperature: four monatomic gases (helium, neon, argon, and krypton), and five polyatomic gases (nitrogen, dry air, carbon dioxide, propane and methane). The molecular weight and specific heat ratio of these gases as given in reference 7 are presented in table I.

To analyze the effect of temperature on frequency of oscillation, three gases (argon, nitrogen, and carbon dioxide) were used. The test apparatus was modified by inserting a heater upstream of the oscillator, installing a thermocouple at the oscillator inlet, and insulating the system. The temperature of the gas was then varied from 75° to 245° F (297 to 392 K) while maintaining constant pressure drop across the oscillator.

3. DISCUSSION OF RESULTS

The principle under which fluidic oscillators operate is that the period of oscillation is proportional to sonic velocity. Thus

$$\frac{1}{f} = K\sqrt{\frac{M}{\gamma T}} \qquad (1)$$

where

f = frequency of oscillation

γ = specific-heat ratio

T = absolute temperature

M = molecular weight

The constant of proportionality (K) is dependent upon geometry of the oscillator including feedback length and switching time (refs. 3, 4, and 5).

3.1 Effect of Pressure Drop on Oscillator Performance

Initial tests conducted with oscillator No. 2 were performed at ambient temperature over a range of pressure drops across the fluidic oscillator. Figure 3 shows the relation between pressure drop and oscillator frequency for carbon dioxide. This curve is typical for all gases used with oscillator No. 2, and illustrates that output frequency varies with pressure drop until choked-flow is reached. Table II shows the measured output frequencies for the other gases tested with oscillator No. 2 during choked-flow conditions and ambient temperature.

Under choked-flow conditions, frequency becomes independent of pressure. Choking in the oscillator occurs at the minimum cross-sectional flow area, which in this case is the outlet vent (fig. 2A). Pressure drops in the tubing and in the fluidic oscillator (fig. 2B) caused the minimum ratio of the measured inlet to outlet pressure for choked-flow to be greater than the theoretical critical pressure ratio, $\left(\frac{\gamma + 1}{2}\right)^{\gamma/(\gamma-1)}$.

3.2 Molecular Weight of Monatomic Gases

A correlation between oscillator output frequency and the molecular weight of monatomic gases was obtained from test results using oscillator No. 2. Figure 4 shows that on a log plot, there exists a linear relation between frequency and molecular weight at ambient temperature. This demonstrates that 1/f for monatomic gases is proportional to $\sqrt{M}$ at constant temperature (eq. 1). Two curves are presented in figure 4, at different pressure levels. The upper curve was obtained at choked-flow conditions where the oscillator becomes pressure independent, while the lower curve was obtained at a constant pressure drop of 9.7 psi (6.7 N/cm^2). The frequency variation from choked conditions and a pressure drop of 9.7 psi (6.7 N/cm^2) ranged from 2.3 percent for krypton to 4.5 percent for helium.

A monatomic gas mixture of helium-xenon was analyzed over a molecular weight range of 31.5 to 44.9 using oscillator No. 1. As shown in figure 5, a linear relation was again obtained between 1/f and $\sqrt{M}$ at a constant (unchoked) pressure drop of 5.0 psi (3.4 N/cm^2) across the oscillator and at ambient temperature.

A comparison of figures 4 and 5 shows that the output frequency for oscillator No. 1 is at a lower level than that of oscillator No. 2. This deviation is mainly due to differences in oscillator geometry; specifically the increase in feedback length. The difference in frequency due to changes in pressure drop is considered small when compared to the changes made in oscillator geometry between oscillator No. 1 and No. 2.

3.3 Molecular Weight of Polyatomic Gases

Polyatomic gases with different specific heat ratios and molecular weights (table I) were analyzed using oscillator No. 2. It was found from test results that output frequency was affected by the specific-heat ratio (γ) of the gas. But a linear relation was obtained when 1/f was plotted against $\sqrt{M/\gamma}$ (fig. 6) which demonstrated that frequency is proportional to sonic velocity under conditions of constant temperature and choked flow. Also shown in figure 6 are the data for the monatomic gases, under identical condi-

tions. Two distinct curves were obtained, one for monatomic gases and one for polyatomic gases. Both curves would pass through the origin if extended to show that $1/f$ is directly proportional to $\sqrt{M/\gamma}$ at constant temperature. The reason for two constants of proportionality, one for monatomic gases and one for polyatomic gases, has not been investigated.

Experimental results from a gas mixture of hydrogen-nitrogen, using oscillator No. 1, are presented in figure 7. These data verify the straight line relation obtained using oscillator No. 2 for polyatomic gases. Since the specific-heat ratios of hydrogen and nitrogen are approximately the same, a linear relation was obtained between $1/f$ and $\sqrt{M}$ over a molecular weight range of 3.4 to 6.8. The tests were conducted at a constant temperature of 70° F (294 K) and with a constant pressure drop of 6.0 psi (4.1 N/cm^2) across the oscillator.

3.4 Temperature Effect

The effect of temperature was measured using oscillator No. 2. Three gases (argon, nitrogen, and carbon dioxide) were used at temperatures ranging from 75° to 245° F (297 to 392 K) at choked flow conditions. As expected from the proportionality of frequency and sonic velocity, a linear relation is seen in figure 8 between f and $\sqrt{T}$ for each of the three gases. It is this linear relation that allows a fluidic oscillator to be used as a temperature sensor (ref. 4).

3.5 Combination Effects

To utilize a fluidic oscillator as a molecular weight sensor, not only must output frequency be measured, but the additional effects of temperature and gas properties must be considered. Data from all gases tested with oscillator No. 2 during choked-flow conditions are plotted in figure 9 to obtain curves of $1/f$ against $\sqrt{M/\gamma T}$. Once again, two distinct straight lines were obtained, one for the monatomic gases and another for the polyatomic gases.

Figure 9 can be rearranged so that molecular weight is plotted against $\gamma T/f^2$ as shown in figure 10. For any one of the gases tested for temperature effects with oscillator No. 2, the value of $\gamma T/f^2$ remained constant within 1 percent for changes in temperature from 75° to 245° F (297 to 392 K) during choked-flow conditions.

4. SUMMARY OF RESULTS

An experimental investigation was performed using two fluidic oscillators of different geometry to sense molecular weight of flowing gases having weights from 4 to 83.8. It was observed that for choked-flow or constant pressure drop across the oscillator, oscillator frequency was proportional to the sonic velocity of the gas used. However, for similar test conditions, the monatomic and polyatomic gases have different constants of proportionality.

Additional tests performed showed that output frequency varied with pressure drop across the oscillator until choked-flow was reached. For choked-flow conditions, the frequency became pressure independent.

It has been demonstrated that a fluidic oscillator can be used as a molecular weight sensor for flowing gases. For accurate measurements of molecular weight, compensation must be made for deviations in temperature and gas specific-heat ratio. If the flow through the oscillator is less than choked-flow, pressure drop across the oscillator must remain constant.

5. REFERENCES

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5. Savkar, S. D.; Hansen, A. G.; and Keller, R. B.: Experimental Study of Switching in a Bistable Fluid Amplifier. Paper 67-WA/FE-37, ASME, Nov. 1967.

6. Prokopius, Paul R.: Use of a Fluid Oscillator as a Humidity Sensor for a Hydrogen-Steam Mixture. NASA TM X-1269, 1966.

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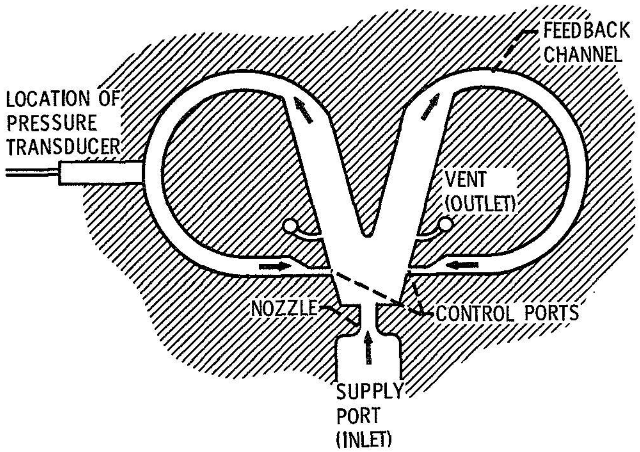
TABLE I. - PROPERTIES OF GASES USED IN OSCILLATOR TESTS

Gas	Molecular weight	Specific-heat ratio
Air (dry)	29.0	1.40
Argon	39.94	1.668
Carbon dioxide	44.01	1.30
Helium	4.00	1.66
Hydrogen	2.00	1.41
Krypton	83.80	1.68
Methane mixture	[a]17.27	1.31
Neon	20.18	1.64
Nitrogen	28.02	1.404
Propane	44.10	1.13
Xenon	131.30	1.66

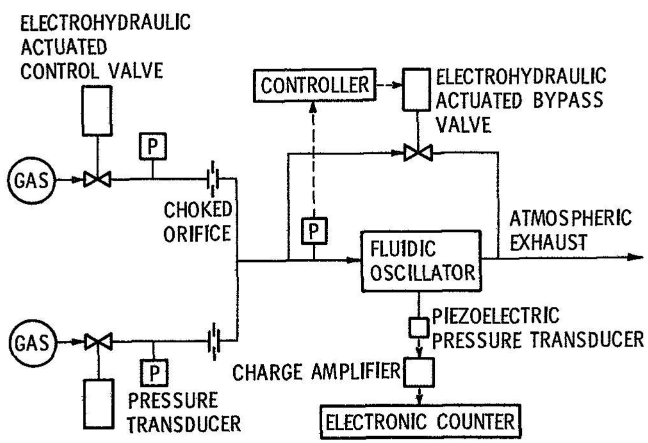
[a]Molecular weight of methane mixture was obtained from chemical analysis.

TABLE II. - OSCILLATOR FREQUENCY OBTAINED WITH OSCILLATOR NO. 2 FOR VARIOUS GASES DURING CHOKED-FLOW CONDITIONS AND AMBIENT TEMPERATURE

Gas	Frequency Hz
Helium	7987
Neon	3567
Argon	2546
Kryton	1762
Methane mixture	3546
Nitrogen	2852
Air (dry)	2804
Carbon dioxide	2201
Propane	2061

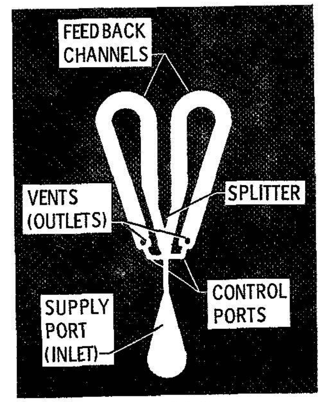


(a) Schematic diagram.

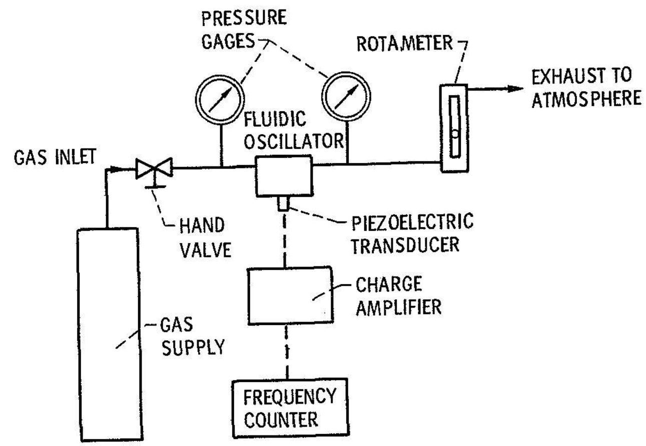


(b) Test rig.

Figure 1. - Oscillator 1.



(a) Schematic diagram.



(b) Test apparatus.

Figure 2. - Oscillator 2.

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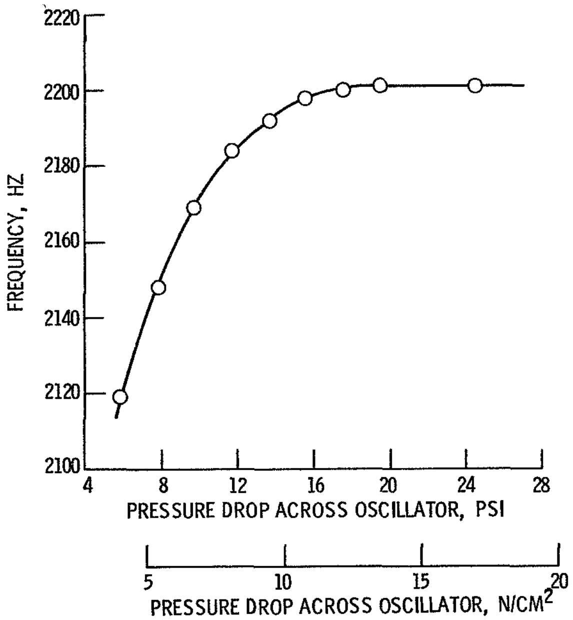

Figure 3. - Typical curve of frequency variation with pressure drop for oscillator number 2. Gas, carbon dioxide; temperature, 71° F (295 K); exhaust pressure, atmospheric.

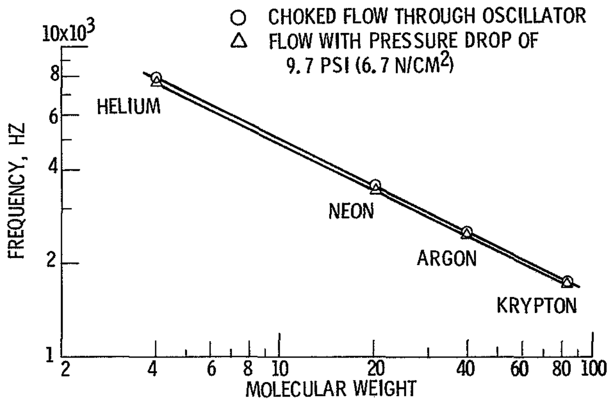

Figure 4. - Variation of frequency with molecular weight for monatomic gases using oscillator number 2. Gas temperature, 71° F (295 K).

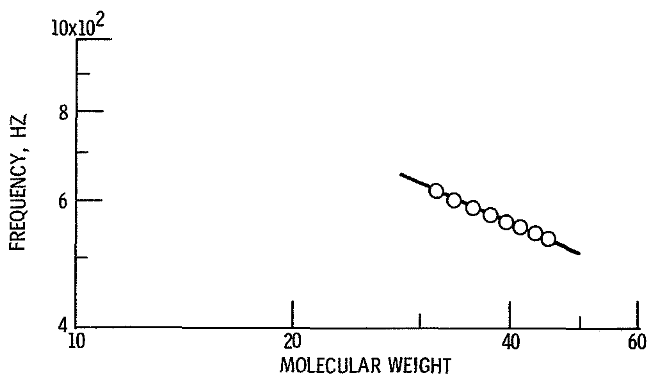

Figure 5. - Oscillator frequency for mixtures of helium-xenon using oscillator number 1 at 70° F (294 K) and constant pressure drop of 5.0 psi (3.4 m/cm²).

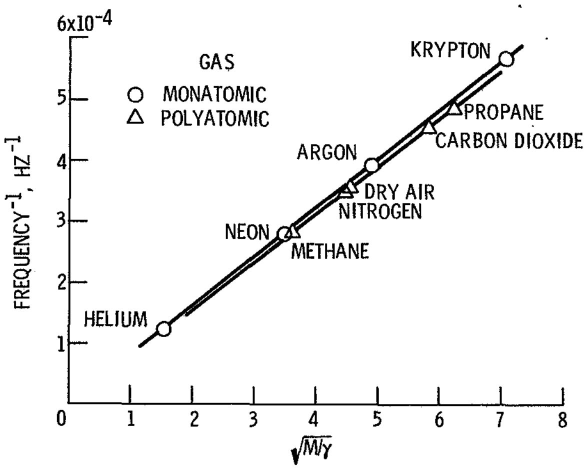

Figure 6. - Effect of various gases on oscillator output frequency using oscillator number 2. Gas temperature, 71° F (295 K); choked flow through oscillator.

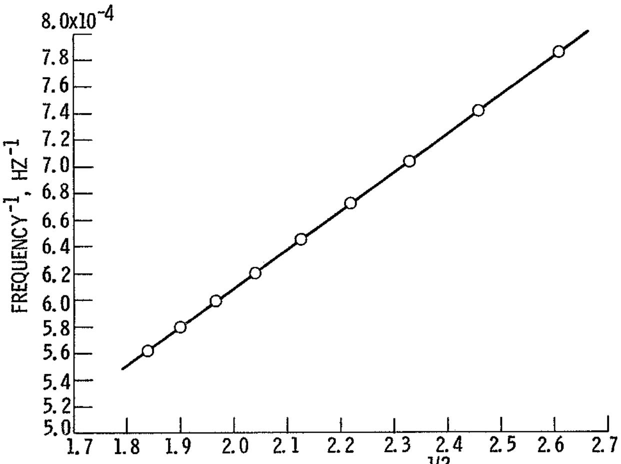

Figure 7. - Oscillator frequency for a hydrogen-nitrogen gas mixture using oscillator number 1 at 70° F (294 K) and a constant pressure drop of 6.0 psi (4.1 N/cm^2) across oscillator.

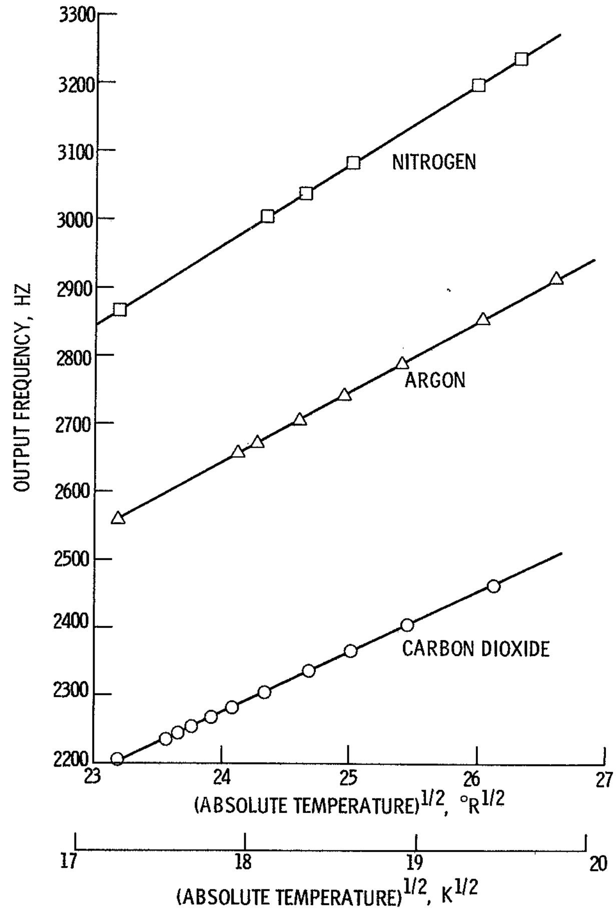

Figure 8. - Temperature effect on oscillator output frequency. Choked flow through oscillator number 2.

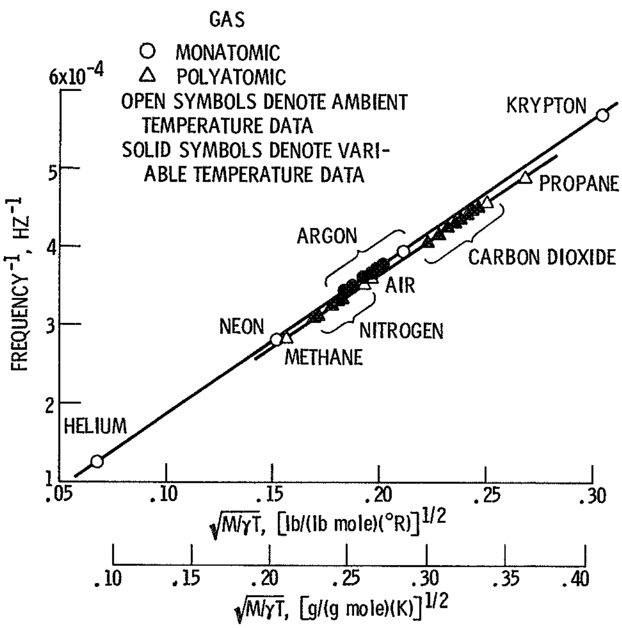

Figure 9. - Effect of temperature on oscillator performance using various gases and oscillator number 2. Choked flow through oscillator.

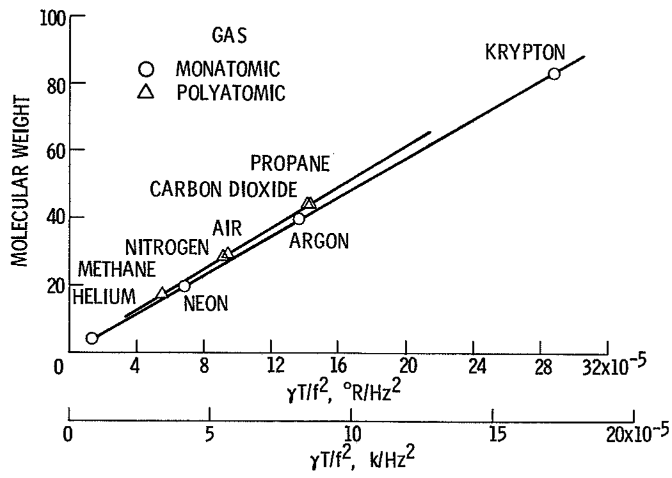

Figure 10. - Summary of oscillator performance. Choked-flow through oscillator number 2.